# The Sudbury Neutrino Observatory—Taking Physics Beyond the Standard Model

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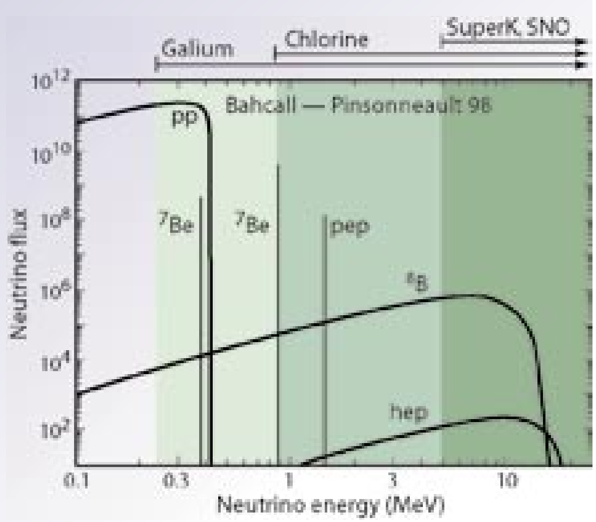
In the 1930s, in an attempt to preserve the conservation of energy in nuclear beta decay, Wolfgang Pauli invented a new particle—the neutrino. This elusive particle has no electric charge and interacts so weakly that it was almost impossible to detect. More than 20 years later, the neutrino was finally observed by a research team from LANL in an experiment at the Hanford reactor. Two years later, a definitive experiment at the Savannah River reactor clearly demonstrated the existence of the neutrino. Subsequent measurements at various facilities indicated that neutrinos come in at least three different types, or "flavors"—electron, muon, and tau. Determining whether neutrinos have mass is an issue of great importance to particle physics, astrophysics, and cosmology. The search for evidence of neutrino mass and the study of neutrino interactions with nuclei has evoked continuous experimental efforts by scientists from LANL for over 50 years. Accelerator-driven neutrino experiments like those performed on the LSND at LANSCE and now the BooNE (which is currently taking data at FNAL in Illinois to definitively test the LSND findings) provide evidence that could indicate that neutrinos do, in fact, oscillate from one type to another and therefore have mass (see *Accelerator Neutrino Experiments on the LSND and MiniBooNE*, p. 131, in this report). We are performing non-accelerator-based experiments using SNO—a terrestrial detector located 6,800 ft underground in an active nickel mine in Ontario, Canada—to understand why solar neutrino fluxes measured in terrestrial detectors fall significantly short of standard solar model predictions.[1] Both accelerator- and non-accelerator-driven neutrino experiments provide important tests that may challenge the Standard Model of electro-weak interactions while searching for neutrino oscillations.

## Resolving the Solar-Neutrino Puzzle

While continuing to probe the neutrino at accelerators, LANL scientists initiated a program of non-accelerator physics that provided alternative means to probe the properties of the neutrino. A high-precision measurement of the spectrum of the electrons emitted in the beta decay of tritium provided a means to search for a very small neutrino mass. This experiment provided a limit on the mass of the electron-type neutrino, which was sufficient to rule out electron-type neutrinos as being the dominant mass in the universe. To dramatically improve sensitivity, scientists shifted the focus of non-accelerator efforts to measurements of solar neutrinos produced 93 million miles away—deep in the nuclear furnace of the sun. LANL played the lead role in a solar-neutrino experiment, known as the Soviet-American Gallium Experiment (SAGE), at the Baksan Neutrino Observatory in the Caucusus mountains of southern Russia.[2] SAGE uses

*Figure 1. The solar-neutrino energy spectrum as computed by Bahcall and Pinsonneault.[3] Terrestrial-solar-neutrino experiments have measured neutrinos from the sun across the entire energy spectrum. The low-energy radiochemical experiments determine an integral flux of solar neutrinos above their respective thresholds. The water Cerenkov detectors, SuperKamiokande (SuperK) and SNO, measure the $^8B$ flux of solar neutrinos directly.*



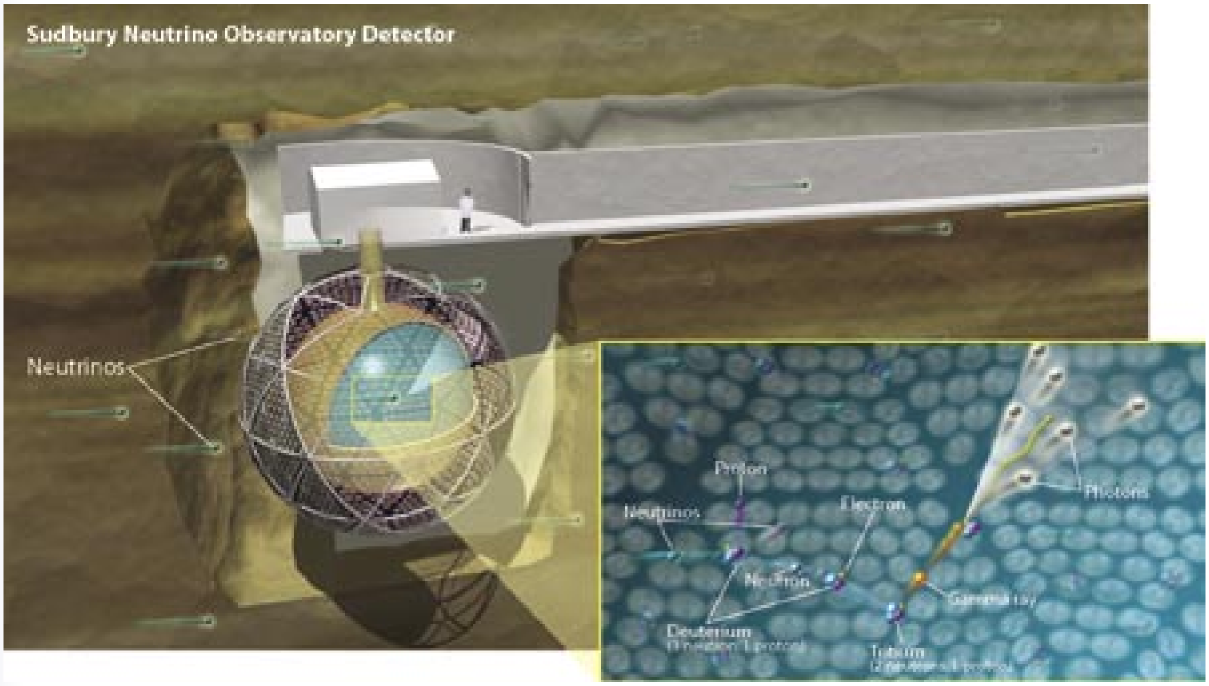



*Figure 2. Three-dimensional rendering of SNO. In one of three neutrino reactions (in the inset) detected by SNO, a neutrino entering the detector interacts with a deuterium nucleus. The reaction produces a proton, neutrino, and neutron. The neutron is captured by another deuterium nucleus, producing a tritium atom in the process. The tritium atom decays and in that process releases a gamma ray, which then collides with an electron. Cerenkov light is emitted and detected by PMTs that line inside of the SNO vessel.*

50 tons of metallic gallium in which the neutrinos that drive the primary energy-producing fusion reaction in the sun whereby two protons (p-p) fuse to form deuterium can transform the $^{71}$Ga nuclei into $^{71}$Ge. The individual atoms of germanium that are formed are chemically extracted and counted when they decay back to $^{71}$Ga. This measurement provided the first determination of the total flux of neutrinos from the sun and produced a very significant finding—the reduction in flux that had been observed in high-energy neutrinos also extends down to low-energy neutrinos. Measurements of the visible solar luminosity determine uniquely how many of the low-energy p-p neutrinos are produced in the sun. The SAGE results are very hard to understand unless neutrinos oscillate and provide a critical ingredient in resolving the puzzle of the missing solar neutrinos.

For more than three decades, solar-neutrino experiments have been performed in parallel with detailed SSM predictions of the solar-neutrino flux and energy spectrum.[3] With data spanning essentially the entire solar-neutrino spectrum (Figure 1), a Solar Neutrino Puzzle (SNP) emerges wherein the fluxes measured in terrestrial detectors fall significantly short of SSM predictions.[1] The SSM is constrained by knowledge of the solar luminosity and is now independently tested using helioseismology. The data are inconsistent with a sun that "shines" based upon our basic notions of stellar evolution and the basic tenets of nuclear and particle physics—which hint of new physics not contained in the present Standard Model of elementary particles. In particular, electron neutrinos born in nuclear fusion reactions powering the sun are thought to somehow transform into different types of neutrinos that go undetected in experiments on the earth—a hypothesis known as *neutrino-flavor transformation.*[4] Because the sun is energetic enough to produce only electron neutrinos and because, until recently, terrestrial detectors are sensitive largely only to electron neutrinos, the SNP can be resolved if sun-born electron neutrinos are somehow transformed to muon and/or tau neutrinos before their arrival on the earth. Testing neutrino-flavor transformation requires a solar-neutrino detector that can detect the disappearance of electron neutrinos and the appearance of muon and/or tau neutrinos.

The SNO experiment may realize the possibility of neutrino-flavor transformations. At the heart of the SNO detector is 1,000 tonnes of ultra-pure heavy water ($D_2O$), which serves as a neutrino target. Neutrino interactions are identified through the production of Cerenkov light detected in an array of 10,000 PMTs (Figure 2). The SNO experiment exploits three unique interactions of $^8$B solar neutrinos on deuterium ($^8$B is an element produced in the sun; it beta decays to produce electron neutrinos):

(CC) $\nu_e + d \rightarrow p + p + e^- - 1.44$ MeV,

(ES) $\nu_x + e^- \rightarrow \nu_x + e^-$, and

(NC) $\nu_x + d \rightarrow p + n + \nu_x - 2.22$ MeV.

The charged-current (CC) interaction can proceed only with electron neutrinos incident on deuterium, whereas the neutral-current (NC) interaction can proceed with equal probability for all active neutrino flavors. The elastic-scattering (ES) interactions are also sensitive to all active neutrino flavors; however, the cross-section is about 6.5 times larger for electron neutrinos than for muon and/or tau neutrinos. The basic concept relies on a direct comparison of the CC flux to that measured in the ES and/or NC channels. A measurement of high ES and/or NC fluxes relative to the CC flux would provide a smoking gun for active neutrino-flavor transformation of electron neutrinos into muon and/or tau neutrinos.

SNO is a heavy-water Cerenkov detector that took over a decade in the making with some 100 collaborators in Canada, the U.S., and the United Kingdom (Figure 2). Its results are best represented in terms of the *flavor content* of the $^8$B solar-neutrino flux depicted in Figure 3. In the simplest sense, the 35-year-old SNP is resolved with data from the SNO experiment. The deficit of electron neutrinos born in the sun is a result of flavor transformation into muon and/or tau neutrinos that are now detected at earth through the unique NC interaction in SNO. Moreover, the total flux of $^8$B neutrinos extracted from this measurement is in very good agreement with predictions of the SSM. Consequently, our basic concepts of how the sun shines appear intact, and we have witnessed the discovery of new physics in the guise of solar-neutrino flavor transformation. We now know that this flavor transformation definitely results because neutrinos have non-zero mass and that neutrino oscillations occur in nature.

## Conclusion

***Present and future plans for SNO***. These milestone results from SNO were obtained while operating the detector during the "pure-$D_2O$" phase from November 2, 1999, through May 28, 2001.[5,6,7] The NC rate of solar neutrinos was deduced by counting the neutrons liberated when neutrinos disintegrate the deuteron. In $D_2O$, this signal ensues from the Cerenkov light produced when these neutrons recapture on deuterium and create 6.25-MeV gamma rays in the process. Significant improvements in precision can be made in the "dissolved-salt" phase in SNO whereby the detector is operated after dissolving 2 tonnes of NaCl into the 1,000-tonne $D_2O$ volume. In addition, because of the multi-gamma cascade associated with neutron capture on chlorine, an additional degree of freedom, or "event isotropy," allows for better separation of the various solar-neutrino signals. The SNO detector has been operating in the dissolved-salt phase since mid May 2001. Results from the dissolved-salt phase have recently been released[8]; these results improve sensitivity to the NC by about a factor of three over the pure-$D_2O$ phase with significant improvement in the constraints on fundamental neutrino parameters (Figure 4).

Ultimately, the CC and NC signals will be independently and simultaneously extracted in SNO by detecting neutrons in a discrete array of neutral current detectors (NCDs) comprised of some 400 m of ultra-low-background $^3$He proportional counters. A research and development program was started over a decade ago at LANL to develop an NCD array with intrinsically low radioactivity and with the capability of operating effectively under water. In collaboration with colleagues at the University of Washington and Lawrence Berkeley Laboratory, we have completed a full-scale construction of the NCD array. Plans are under way to deploy the array into SNO now that the dissolved-salt phase is complete.

***New-generation experiments.*** With data from the SNO experiment, the 35-year-old SNP is resolved, and we now know that neutrinos have mass and that neutrino oscillations occur. Improvements in precision measurements at SNO will better define the neutrino mass and mixing parameters and further test our models of stellar evolution. Nonetheless, fundamental questions remain for the neutrino sector that cannot be addressed in existing experiments.

The evidence for neutrino oscillations described above constrains the flavor-mixing parameters but only for the splitting of the mass between the different neutrino states. Determining the absolute mass scale for the neutrinos (which is now known to be very small relative to the other elementary particles in nature) is also interesting. One exciting possibility for determining the absolute scale of neutrino mass is zero-neutrino double-beta decay. Two-neutrino double-beta decay is a second-order weak process that has been observed

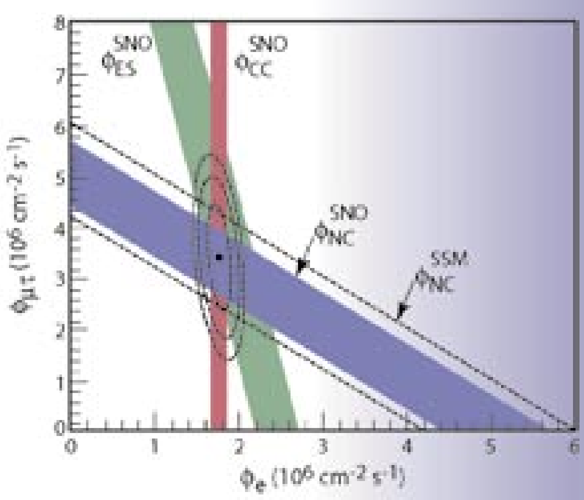
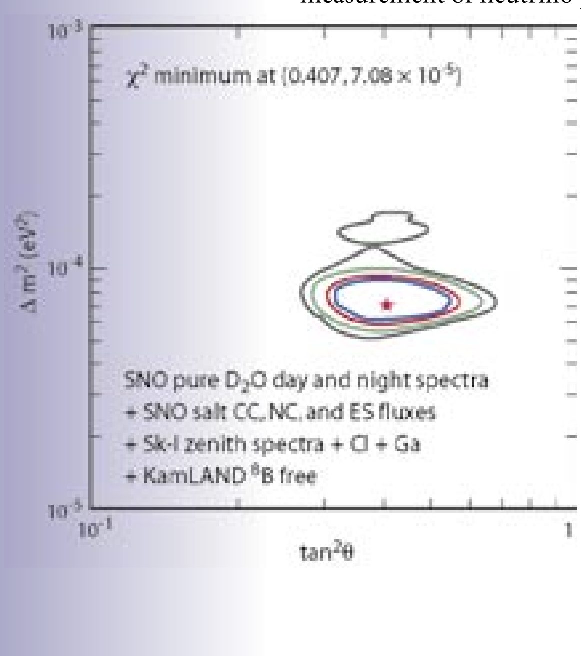



*Figure 3. Flavor-content analysis of the $^8$B solar-neutrino flux based upon data from the SNO experiment. Two-thirds of the electron neutrinos born in the sun disappear because of active neutrino-flavor transformation whereby they reappear as muon and/or tau neutrinos in the SNO detector. The total flux of $^8$B neutrinos is in very good agreement with SSM calculations.*

although it is very rare. A typical half-life is $10^{20}$ years, which is long compared to the age of the universe (~ $10^{10}$ years). A more interesting process, if it exists, is neutrinoless double-beta decay. This process, where no neutrinos are emitted, requires special characteristics of the neutrino and incorporates a two-step process. In both steps of this exchange, an electron would be emitted; however, no neutrino is released. For the exchange to take place, there must be no distinction between a neutrino and an anti-neutrino. If the neutrino has this property, we refer to it as a *Majorana* neutrino. Additionally, neutrinoless double-beta decay requires that neutrinos be the massive Majorana flavor. The Majorana Project at LANL will use 500 kg of enriched $^{76}$Ge to search for this rare process with unprecedented precision.

In addition to the Majorana project, new research and development efforts are also under way at LANL to obtain a detector that can detect low-energy solar neutrinos in real time. About 90% of the solar-neutrino flux is contained below an energy threshold of 1 MeV, which is far below the achievable threshold of a Cerenkov detector such as SNO. A detector with such low-energy capability would serve as the best means for a precision measurement of neutrino parameters and would test models of stellar evolution at the 1% level. Interestingly enough, such detectors, including perhaps the Majorana detector, could serve a valuable dual role. If the intrinsic radioactivity of these detectors can be achieved with a very-low-energy threshold, then they can also be used to intensively search for the missing energy (or dark matter) of the universe.

*Figure 4. Constraints on the solar-neutrino mass and mixing parameters based on a global fit to all existing solar-neutrino and reactor-neutrino data. The central star indicates the best-fit value as indicated by the parameters found at minimum chi-square. Contours are shown at the 90%, 95%, 99%, and 99.73% confidence levels.*

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